

p Note # 466
J. Hangst

CONSIDERATIONS ON THE LITHIUM LENS FAILURE DURING FILLING ON 7 JUNE, 1986

Background:

The titanium jacket of lens #7 ruptured during filling, releasing liquid lithium through the lens cooling circuit. The lens was at a temperature of approximately 200°C, and the liquid lithium pressure was 3600 psi. Room temperature helium gas was being used to cool the lens when it failed. In this note we consider the stresses in the lens at the time of the failure, and the titanium strength under the conditions above.

Stress:

The simple stress on a tube with uniform internal pressure P, radius r, and thickness t is

$$\sigma = \frac{Pr}{t}$$

If we take

$$P = \text{failure pressure} = 3600 \text{ psi}$$

$$r = 0.787" / 2 = 0.3935"$$

$$t = 0.395"$$

$$\text{then } \underline{\sigma = 35863 \text{ psi}}$$

Ultimate Stress of Ti 6AL4V:

The Titanium Alloys Handbook gives, for bars and forgings of annealed 6AL4V of diameter less than 3" (MIL-T-9047), (Figure 1)

$$F_{tu} = 130 \text{ ksi} \quad (> 99\% \text{ of samples})$$

for the ultimate tensile stress. The manufacturer's certifications (Figure 2) give

$$F_{tu} = 168,336 \text{ psi}$$

The analysis of the Charles C. Kawin Company, a metallurgical laboratory which examined the failed lens, gives

$$F_{tu} = 159,720 \text{ psi}$$

Other Factors

Clearly, the stress due to the pressure in the tube should not have been large enough to break the high-strength titanium. But there are other factors which may have contributed to the demise of this lens.

1. Lack of Weld Penetration

Photomicrographs taken by Kawin reveal a lack of penetration in the conductor tube to end cap weld (Figure 3). This lack of penetration appears to be up to 1/2 the thickness of the tube in one photograph (it may be larger at other sections). This would increase the stress in the tube to $\sigma = 71726 \text{ psi}$. There is probably also a stress concentration factor at this notch-like weld.

2. Thermal Stress

The thermal tangential stress for a hollow cylinder of outer radius R and inner radius r_o with temperature gradient ΔT across its thickness is (Reference 2)

$$\sigma_{\theta}(r) = \frac{e\alpha\Delta T}{2(1-\nu)\ln(R/r_o)} [1 - \ln \frac{R}{r} - \frac{r_o^2}{r^2 - r_o^2} (1 + \frac{R^2}{r^2}) \ln(\frac{R}{r_o})]$$

where e is Young's modulus

α is linear expansion coefficient

ν is Poisson's ratio

The maximum of this expression is at $r=R$

$$\sigma_{\theta\max} = \frac{e\alpha\Delta T}{2(1-\nu)\ln(R/r_o)} [1 - \frac{2r_o^2}{R^2 - r_o^2} \ln \frac{R}{r_o}]$$

for titanium, from Reference 1

$$e = 14.24 \times 10^3 \text{ ksi at } 200^\circ\text{C (400°F)}$$

$$\alpha = 5.4 \times 10^{-6} \text{ in/in/}^\circ\text{F at } 200^\circ\text{C}$$

$$\nu = 0.31$$

For the conductor tube design thickness

$$R = 0.433"$$

$$r_o = 0.3935"$$

$$\text{We get } \sigma_{\theta\max} = 21.6 \text{ ksi} \quad (\Delta T = 400^\circ\text{F})$$

Assuming 1/2 thickness weld penetration,

$$r_o = 0.3935$$

$$R = 0.41325$$

We get $\sigma_{\theta\max} = \underline{21.9 \text{ ksi}}$ ($\Delta T = 400^\circ\text{F}$)

Total Stress

If we add the worst case thermal stress to the worst case pressure stress, we get

$$\sigma_{\text{tot}} = 93.6 \text{ ksi}$$

3. Temperature Effect on F_{tu}

From Reference 1, the room temperature ultimate stress of Ti 6AL4V is reduced by a factor of 0.8 at $T = 400^\circ\text{F}$. This gives:

MIL SPEC	$F_{tu} = 104 \text{ ksi}$
Kawin	$F_{tu} = 128 \text{ ksi}$
Mfg	$F_{tu} = 135 \text{ ksi}$

Conclusions

Although the calculated stresses in no case exceed the ultimate strength, we are dangerously close to the MIL SPEC strength limit. A stress concentration factor of 1.44 is required to exceed the manufacturer's claimed strength.

This may not be unreasonable for the geometry at hand. *Add here*

A "healthy", properly welded lens should not have broken under these conditions (assuming there are no other major effects). An attempt to x-ray the suspect weld on a new lens jacket proved fruitless; the weld is obscured by the outer conductor and septum tubes.

In addition, it is probably not necessary to reach the ultimate stress to cause the type of brittle failure observed.

An attempt will be made to minimize the ΔT on the titanium during filling. The lens should be cooled by natural conduction and convection when it is at high temperature. Helium will be employed only when natural cooling slows to an unacceptable rate.

References

1. Titanium Alloys Handbook, Metals and Ceramics Information Center, Battelle Columbus Laboratories, 1972.
2. Rust, James H., Nuclear Power Plant Engineering, Haralson Publishing, 1979.

TABLE 5-4:3. MECHANICAL AND PHYSICAL PROPERTIES OF Ti-6Al-4V (BARS AND FORGINGS)

Specification		MIL-T-9047		Bars and forgings							
Form		Annealed		Solution-treated and aged							
Condition	Width, in.	a	0.5001-8.000	1.001-4.000	4.001-8.000	1.501-4.000	4.001-8.000	2.001-4.000	4.001-8.000	3.001-8.000	4.001-8.000
Thickness or diameter, in.	< 3.000	< 0.5000	0.5001-1.000	1.001-1.500	1.501-2.000	2.001-2.500	2.501-3.000	3.001-3.500	3.501-4.000	3.001-4.000	3.001-4.000
Basis		S	S	S	S	S	S	S	S	S	S
Mechanical properties:											
F_{tu} , ksi	130	160	135	150	150	145	145	140	135	130	130
F_y , ksi	120	150	145	140	140	135	135	130	125	125	120
F_c' , ksi	126	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
F_w , ksi	80	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
F_{br} , ksi:											
$(e/D = 1.5)$	196	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
$(e/D = 2.0)$	248	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
F_{br}' , ksi:											
$(e/D = 1.5)$	174	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
$(e/D = 2.0)$	205	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
ϵ , percent:											
In 4D	10	.....	10	10	10	10	10	10	10	10	10
L .....		.....	10	10	10	10	10	10	10	10	10
L/T .....		.....	10	10	10	10	10	10	10	10	10
E , 10^3 ksi									16.0	16.0	16.0
E_c , 10^3 ksi									16.4	16.4	16.4
G , 10^3 ksi									6.2	6.2	6.2
μ									0.31	0.31	0.31
Physical properties:											
ω , lb/in. ³									0.160	0.160	0.160
C, Btu/(lb)(F)									See Figure 5-4:1.	See Figure 5-4:1.	See Figure 5-4:1.
K, Btu/[(hr)(ft ²)(F)/ft]									See Figure 5-4:1.	See Figure 5-4:1.	See Figure 5-4:1.
a, 106 in./in./F											

^aValues apply to sections up to 3 inches thick, with a maximum cross-sectional area of 10 square inches.



TICO TITANIUM
A DIVISION OF FRANKEL COMPANY, INC.
24581 CRESTVIEW COURT • FARMINGTON, MI 48018
(313) 478-4700
TELEX NO. TICO DN FMHL 23-0163

Certificate of Tests

TO: FERMI LAB
RECEIVING DEPT
BATAVIA IL 60510

DATE: 7/13/84
CUSTOMER P. O. NO.: 13675

ATTN:

S.O. NO.: 13675

HT NO 693
SPEC AMS 4928H
DESC 1" DIA X5 3/4" 4#

HYDROGEN .003 final
ALUMINUM 6.42
VANDIUM 3.68
IRON .22
OXYGEN .18
NITROGEN .012
CARBON ,006
YTTIRUM .002
OTHERS less than .040

TENSILE 168336
YIELD 15316
EL 18
RA 51.3

ANNEALED 1350F 2HRS A.C.

ULTRASONIC MIL I 8950B CLASS A PASSED
STATIC NOTCH 170000psi 5hr min passed

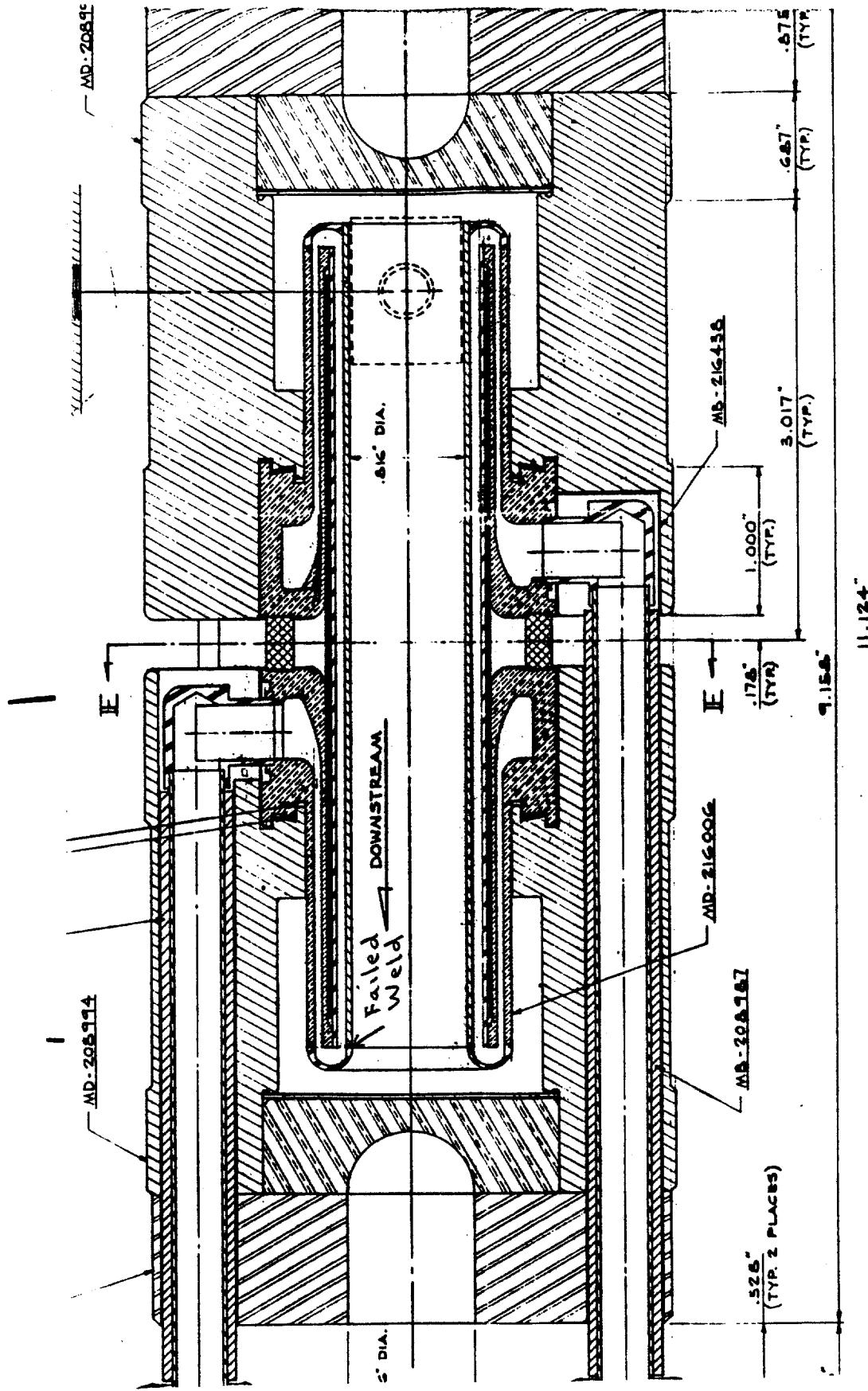
Figure 2

I CERTIFY THAT THE CHEMICAL ANALYSIS AND PHYSICAL TEST RESULTS APPLYING ON THE ABOVE ORDER NUMBER ARE CORRECT AND TRUE TO THE BEST OF OUR KNOWLEDGE AND BELIEF.

TICO TITANIUM
A DIVISION OF FRANKEL COMPANY, INC.
24581 Crestview Court • Farmington, MI 48018

By *[Signature]*

Figure 3



SECTION B-B

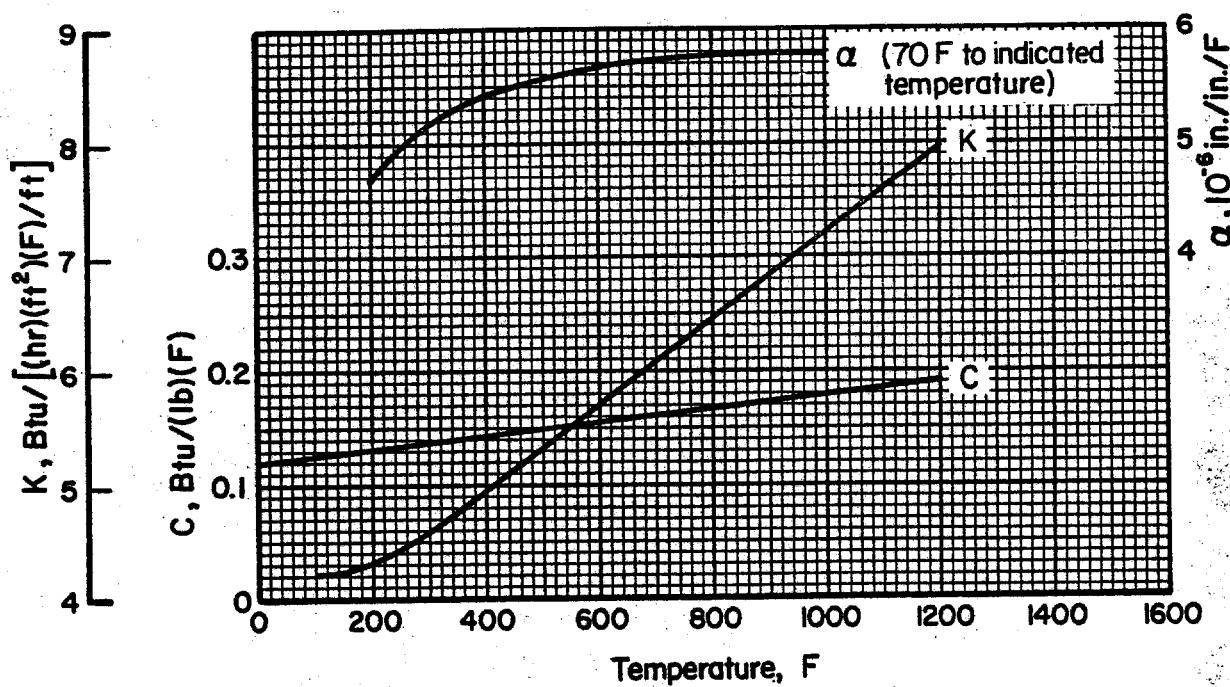


FIGURE 5-4:1. EFFECT OF TEMPERATURE ON THE PHYSICAL PROPERTIES OF Ti-6Al-4V

From Reg. 1

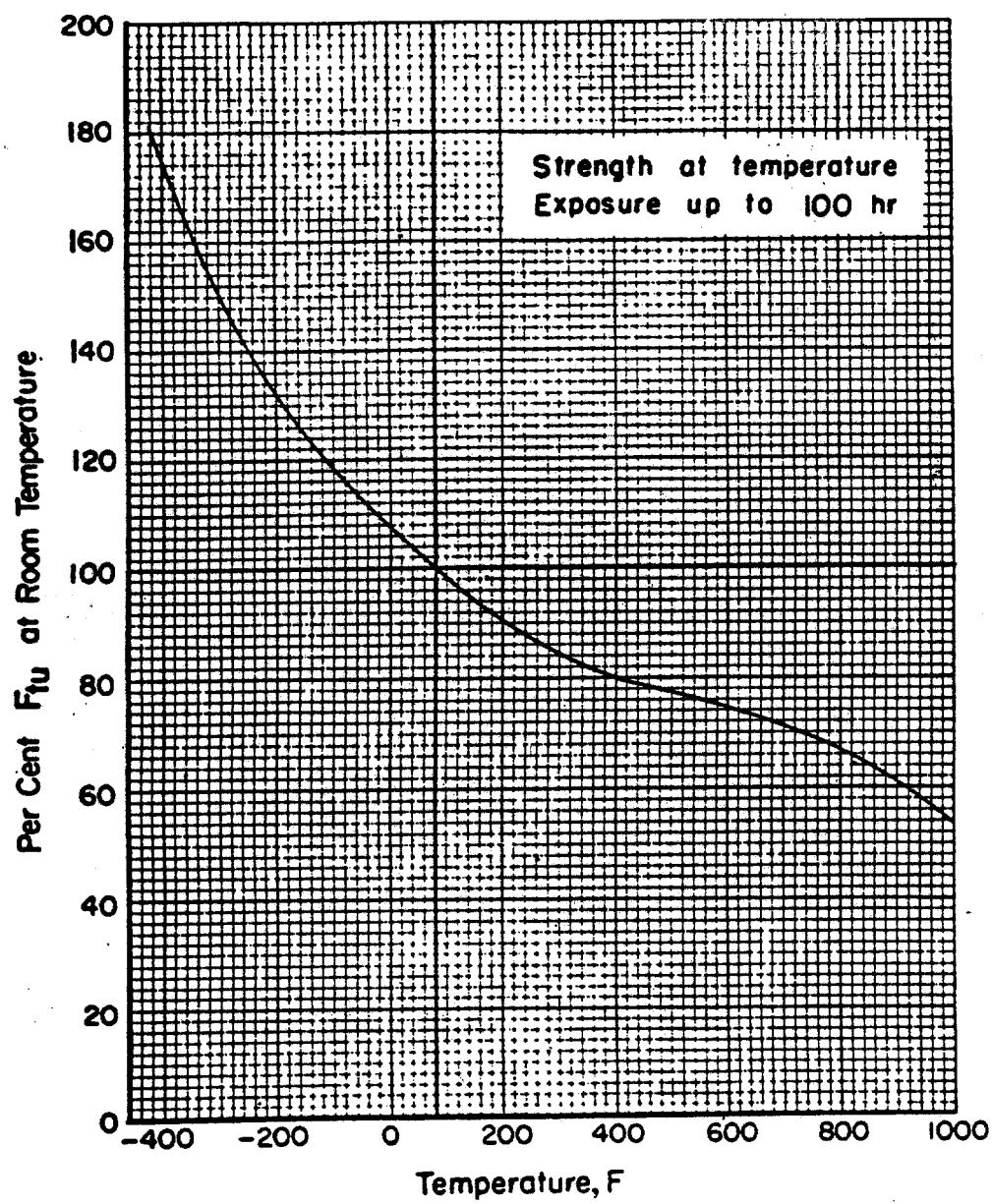


FIGURE 5-4:2. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF ANNEALED Ti-6Al-4V (SHEET AND BAR)

From Ref. 1

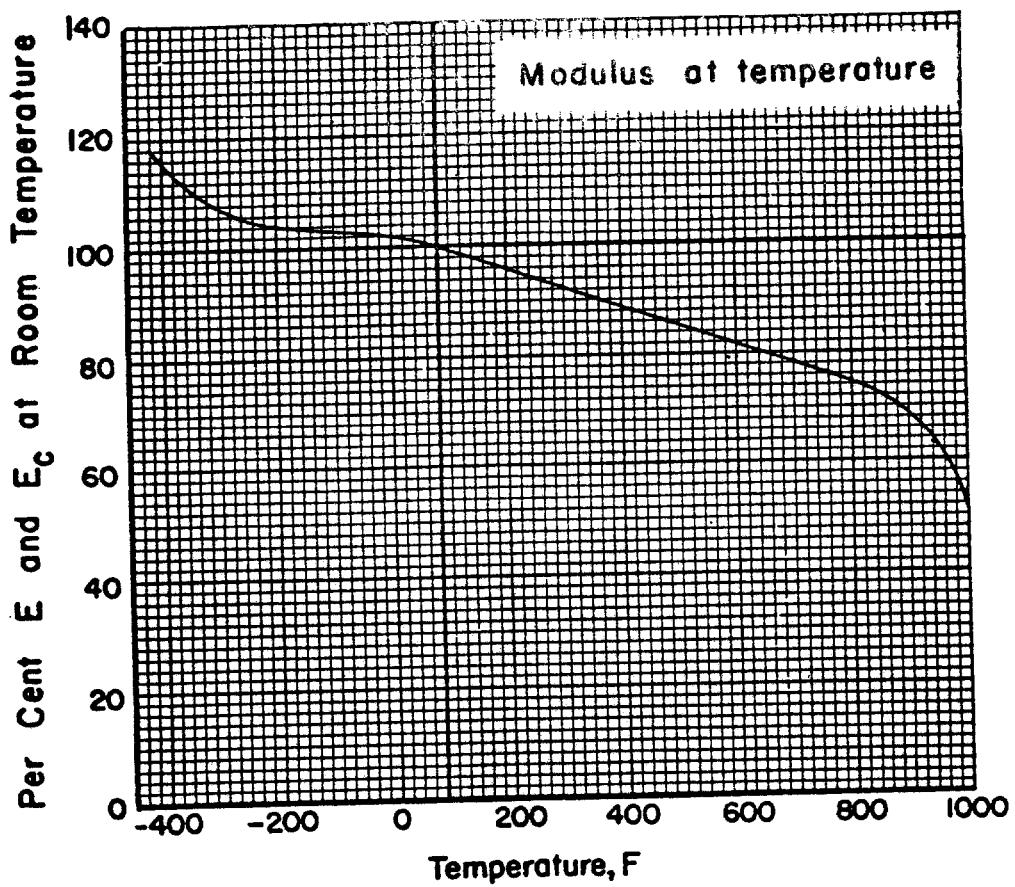


FIGURE 5-4:8. EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULUS (E AND E_c) OF 6Al-4V ANNEALED TITANIUM ALLOY (SHEET AND BAR)

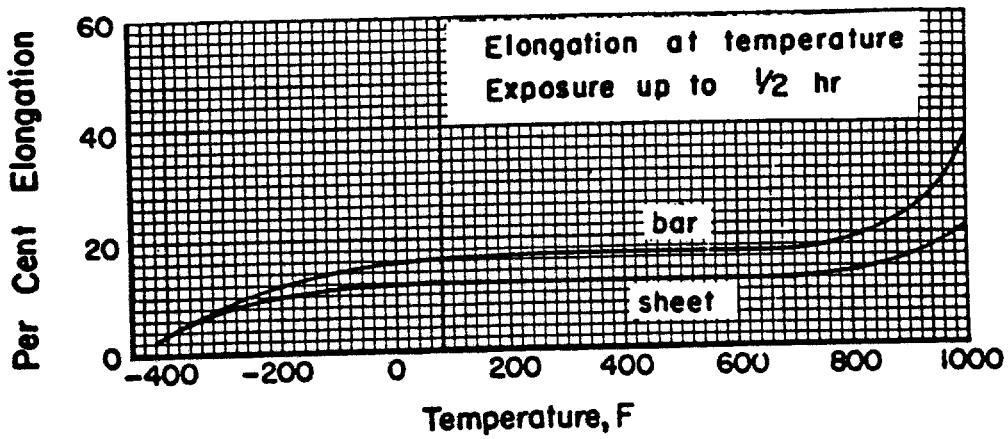


FIGURE 5-4:9. EFFECT OF TEMPERATURE ON THE ELONGATION OF ANNEALED Ti-6Al-4V (SHEET AND BAR)

From Ref. 1